Stochastic Late Accretion on the Earth, Moon and Mars

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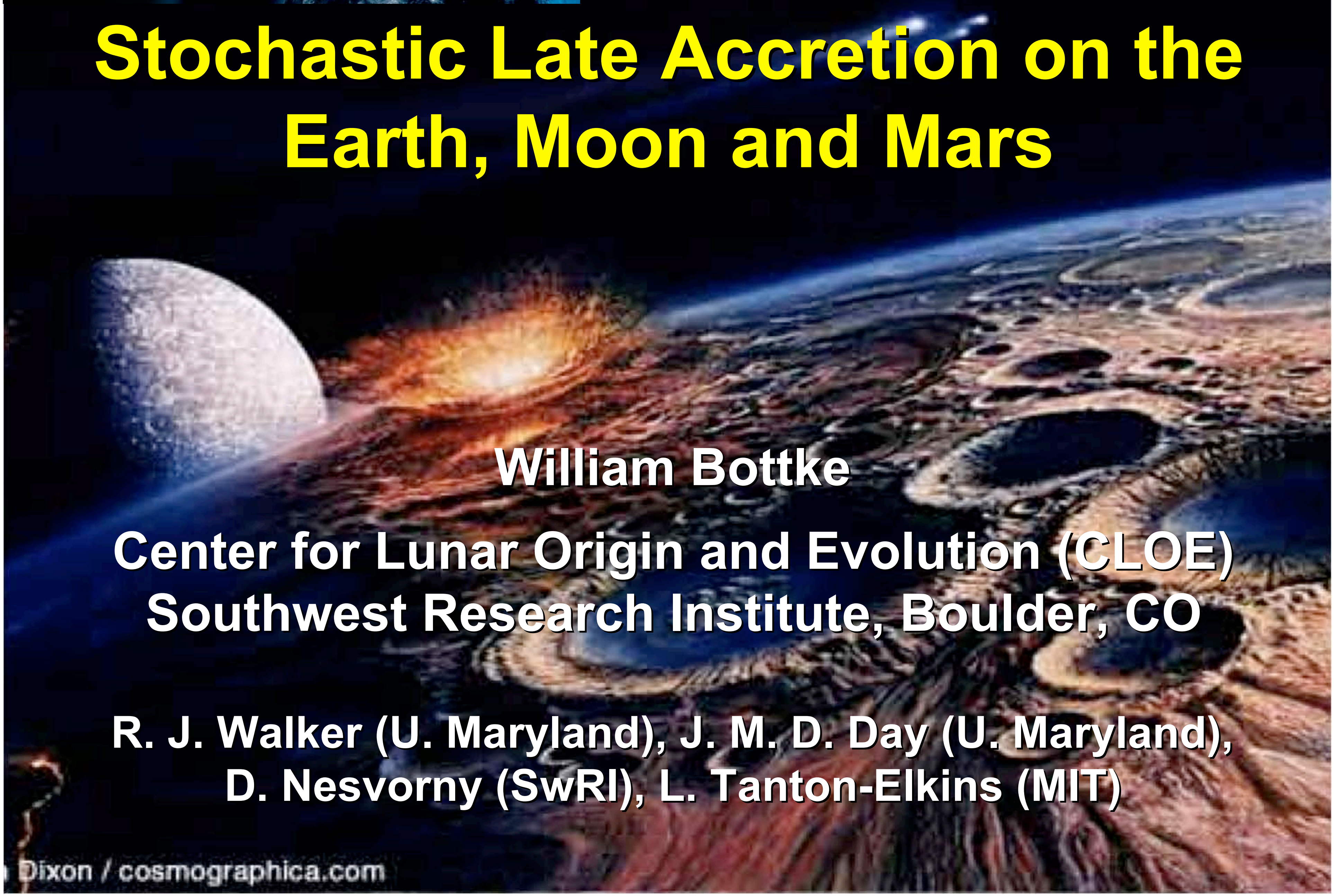
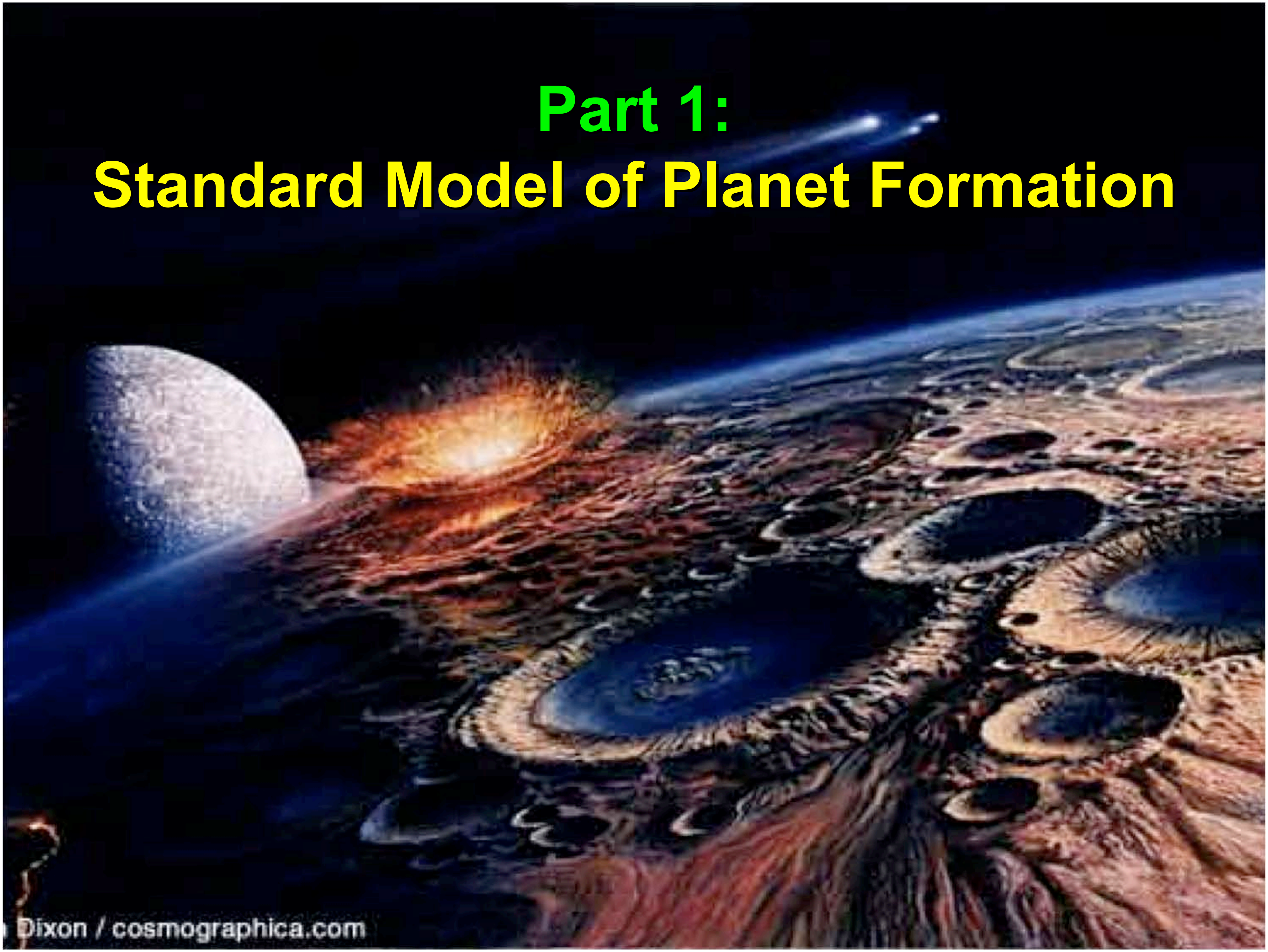


Why Study the Moon?

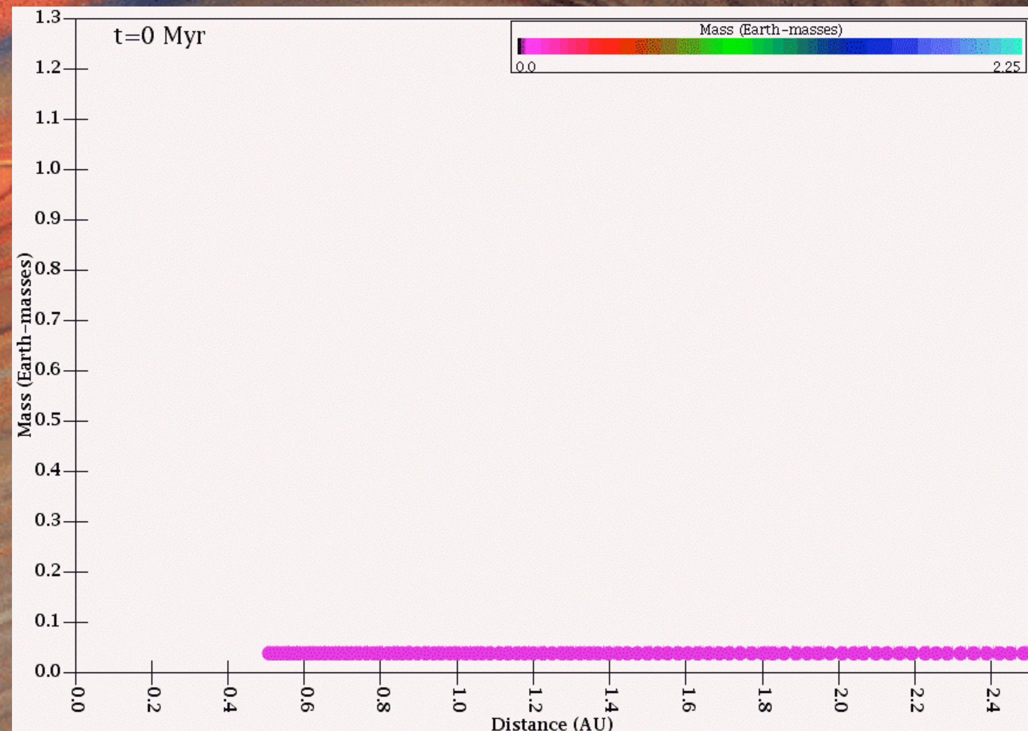
- The Moon itself is fascinating, but it is also a "Rosetta Stone" for telling us about:
  - The unknown nature of the primordial Earth!
  - The critical last stages of planet formation throughout the solar system!

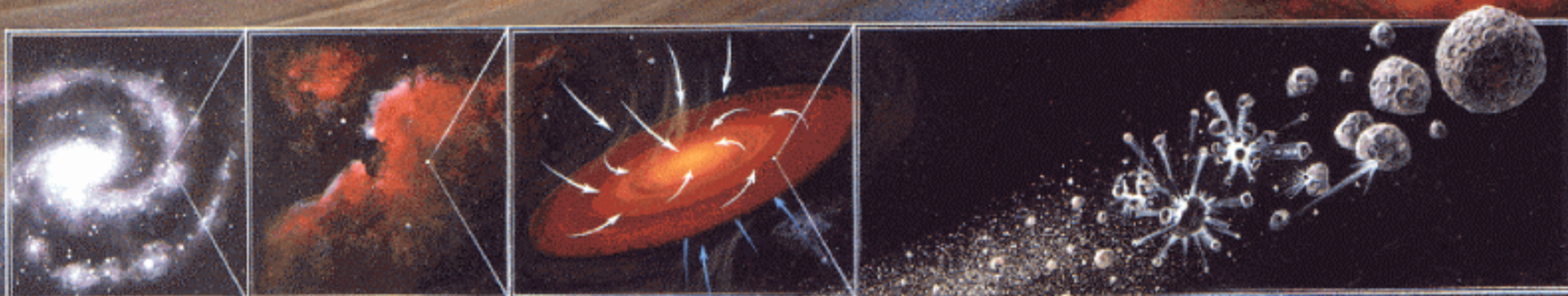
Part 1:
Standard Model of Planet Formation



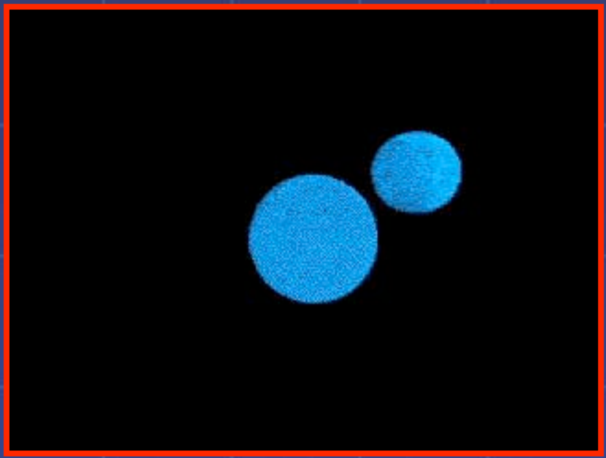
Planetesimal and Planet Formation

- Disk particles come together by gravity.
- Collisions make larger objects by "accretion".
- Planetary embryos collide and eventually create planets.





Outcomes from the Moon-Forming Impact

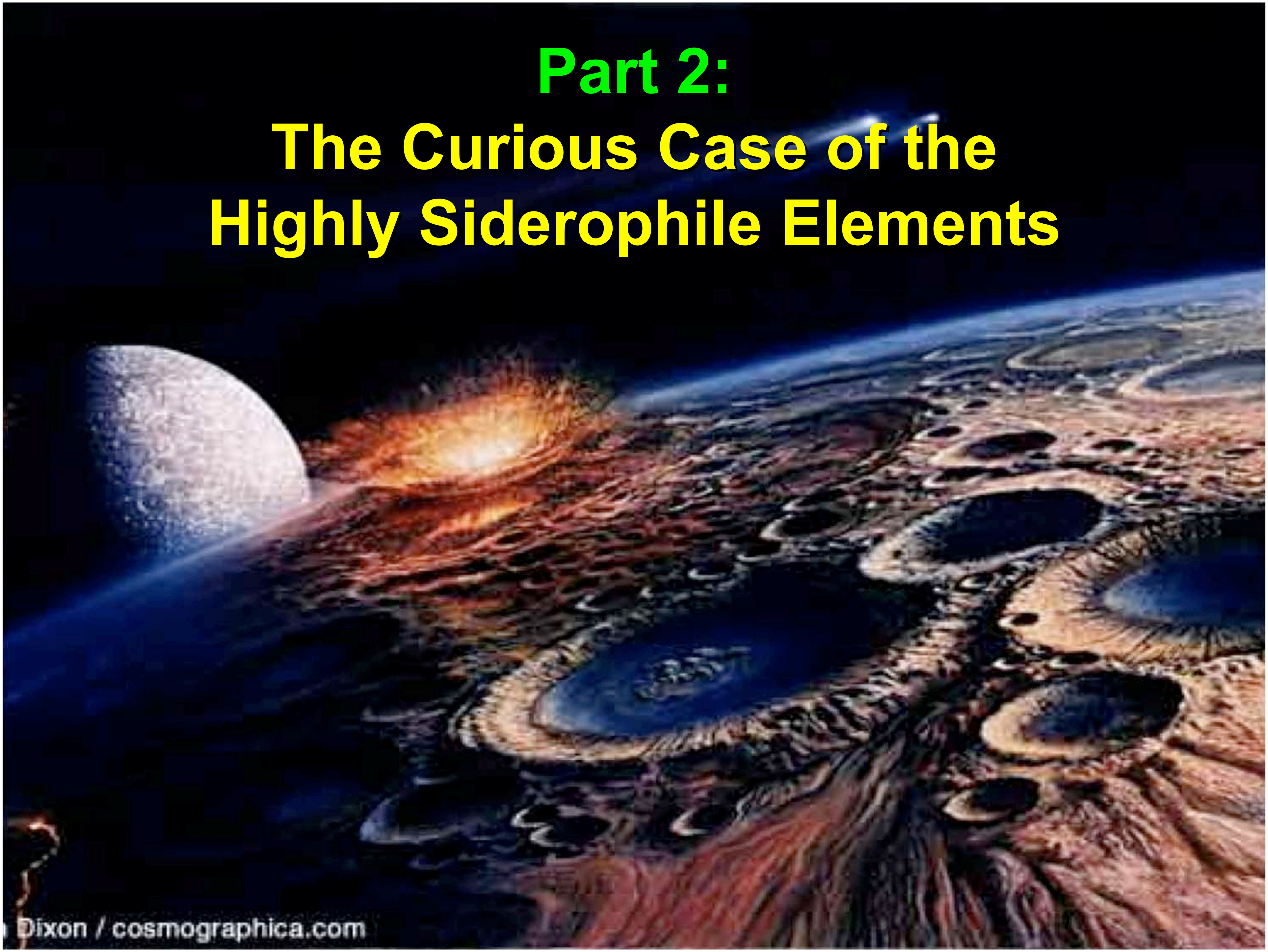


- Giant impact leads to last differentiation event on the Earth and Moon near ~60 (+90, –10) My after the formation of CAIs at 4.56 Ga.
- Final phase of core formation and global magma oceans occur on both worlds.
- A thick stable lunar crust grows over time. The Earth also grows a crust that can be recycled by plate tectonics.

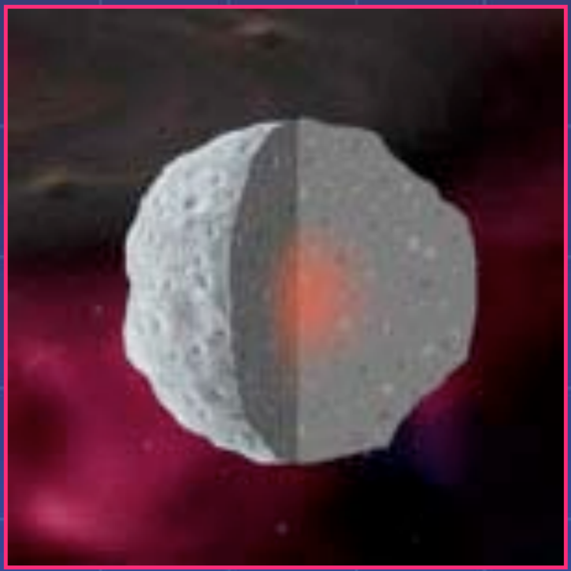
That's It, Right?

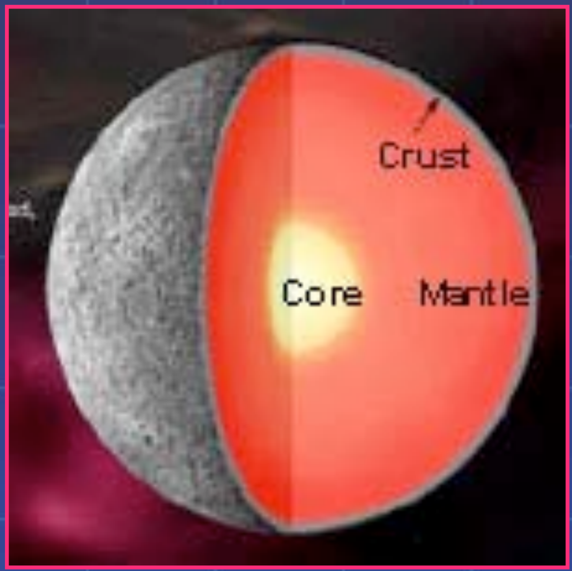
- Are the Earth and Moon effectively done in terms of their internal structure being influenced by impacts?

Part 2:
The Curious Case of the Highly Siderophile Elements



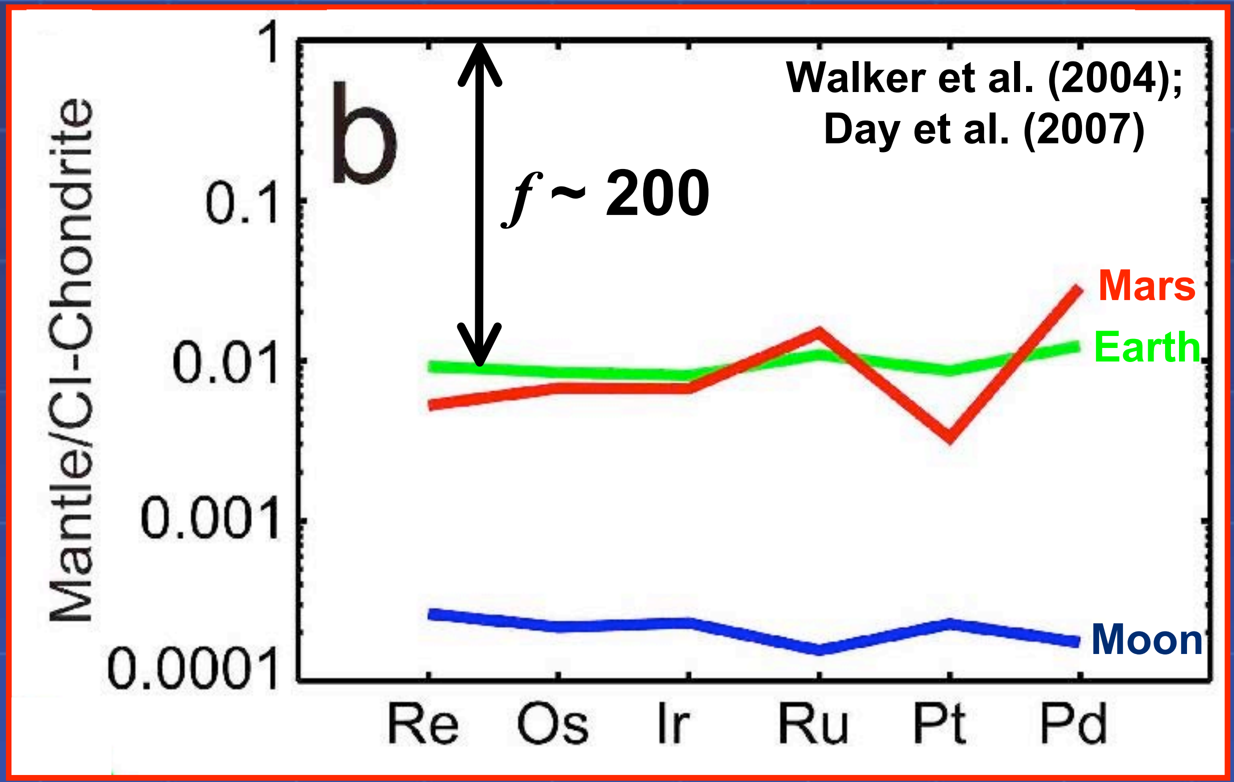
Highly Siderophile Elements (HSEs)





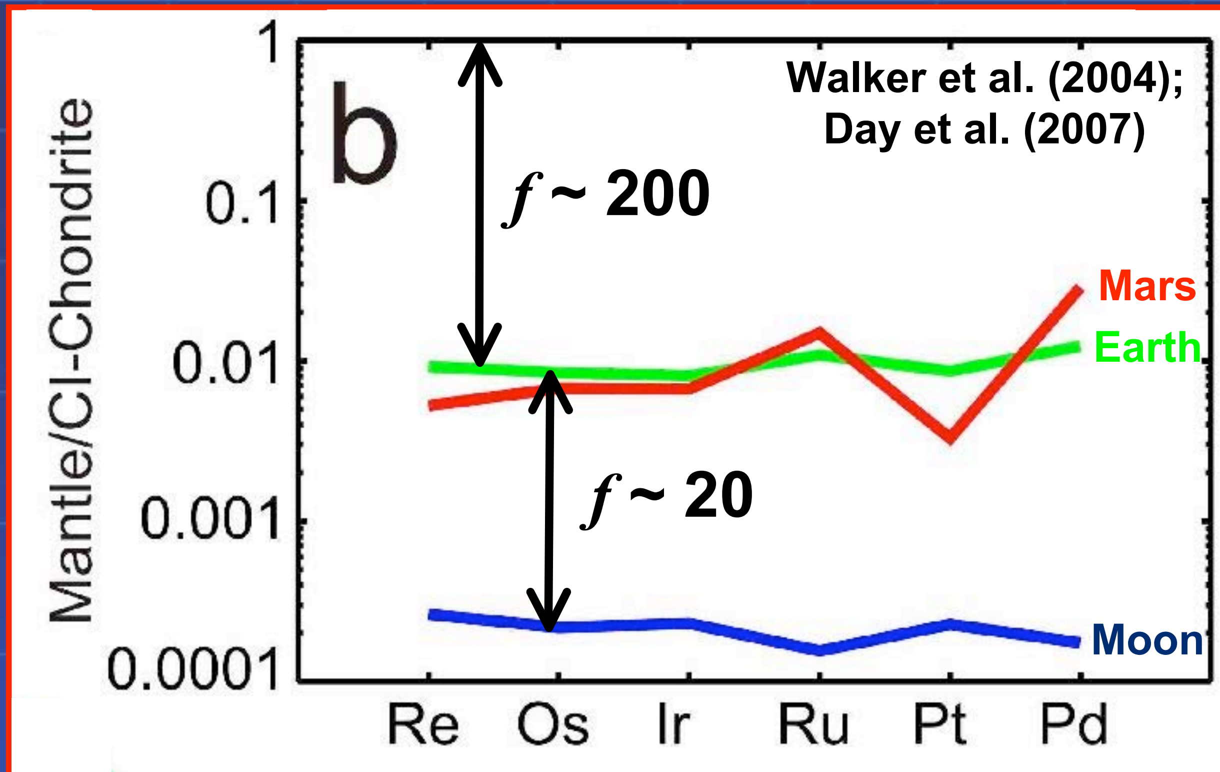
- HSEs (Re, Os, Ir, Ru, Pt, Rh, Au) are metals with high metal-silicate partition coefficients (> 10^4).
- During primary accretion, differentiation, and core segregation, HSEs <u>should</u> go to a planet's core, never to be seen again.

Mantle HSEs from Earth, Moon, and Mars



- Earth's ancient mantle only depleted in HSEs by factor of ~200 compared to chondrites. **Why?**
- It also had chondritic relative proportions (i.e., it is pretty "flat" compared to standard chondrite abundances).

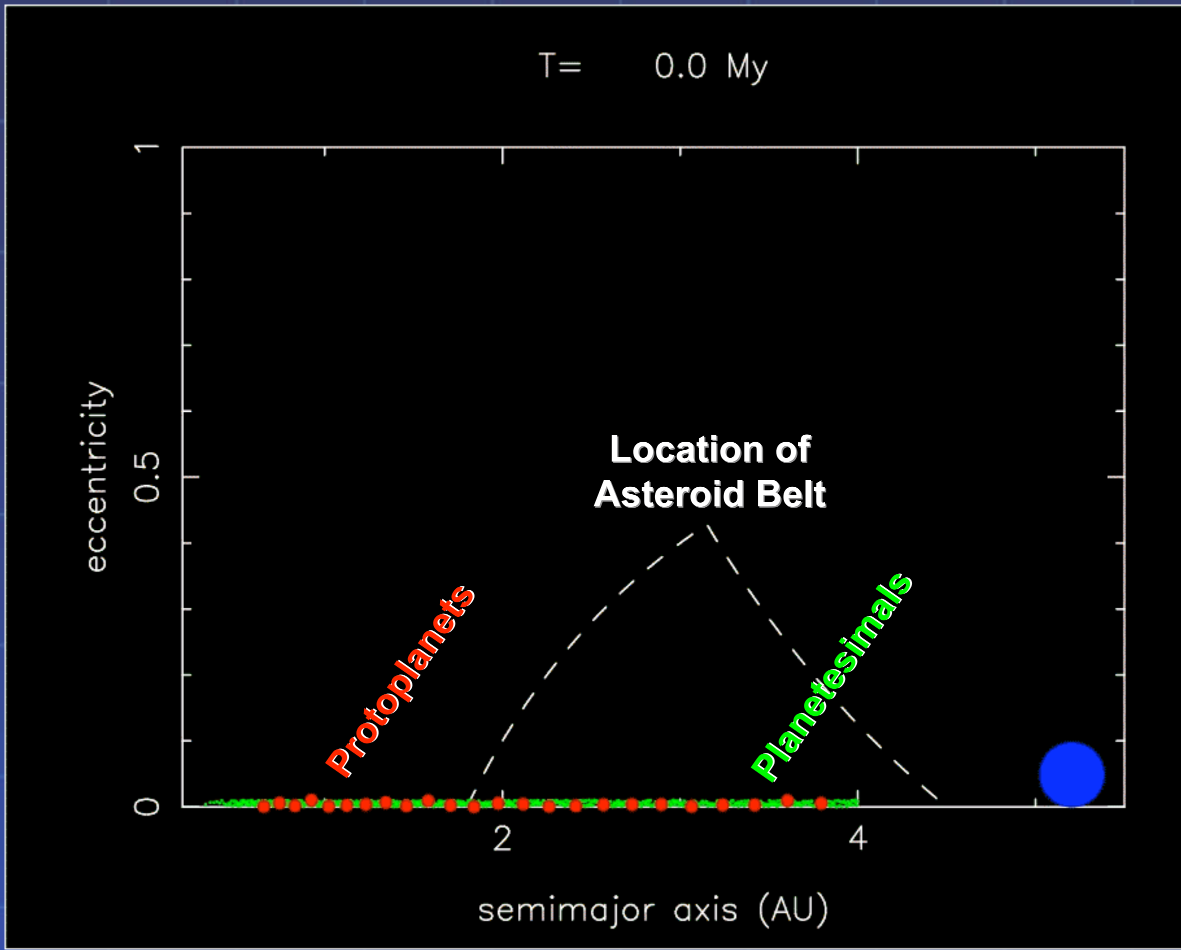
Mantle HSEs from Earth, Moon, and Mars

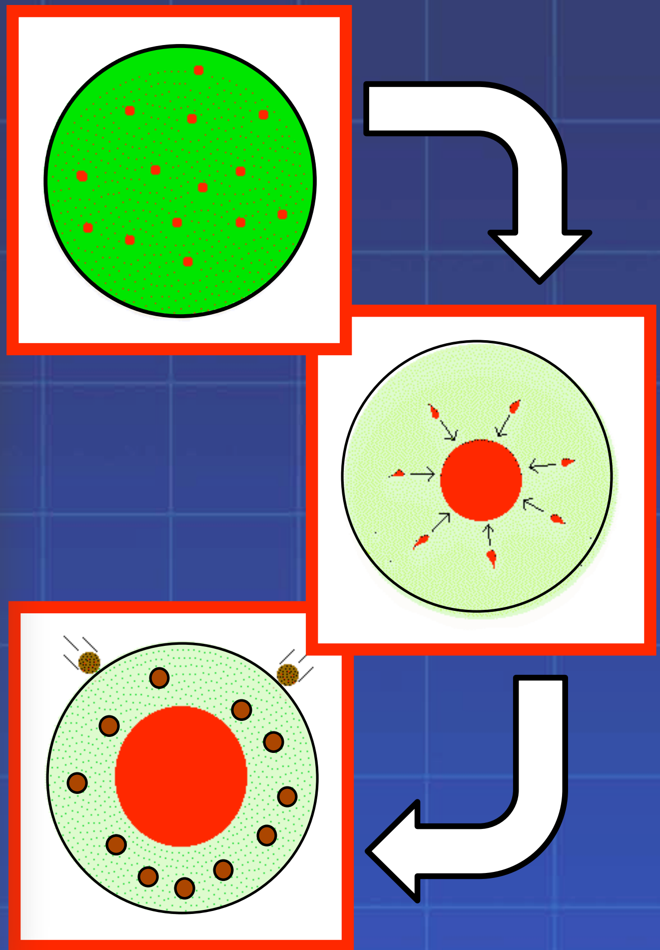


- The Moon is a factor of ~20 lower than the Earth in HSEs, but also has chondritic relative proportions. **Why?**

Part 3:
Late Accretion on the Earth and Moon

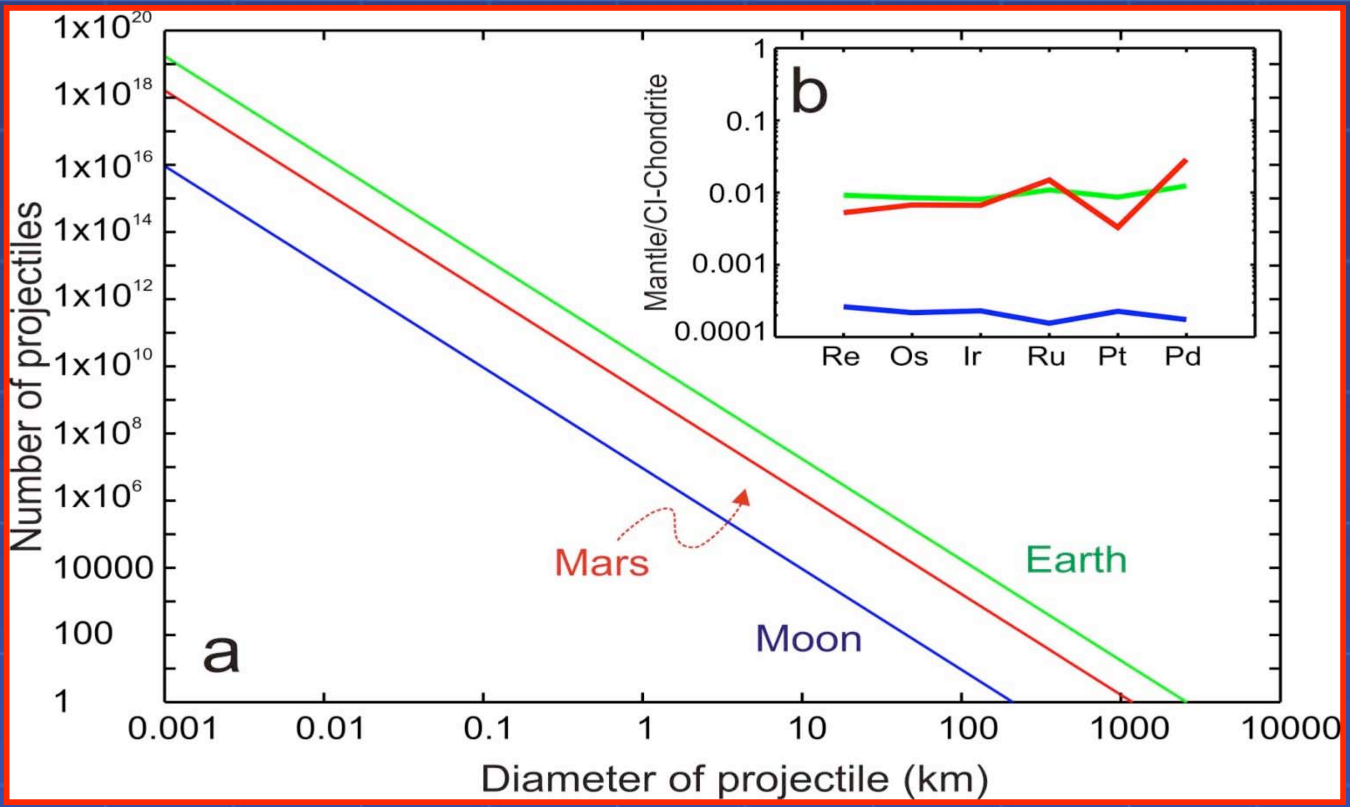
What is "Late Accretion"?





- Addition of "chondritic" material to the Earth during end stages of, or following core formation (Chou, 1978).

How Much Mass is Needed for Earth, Moon, Mars?

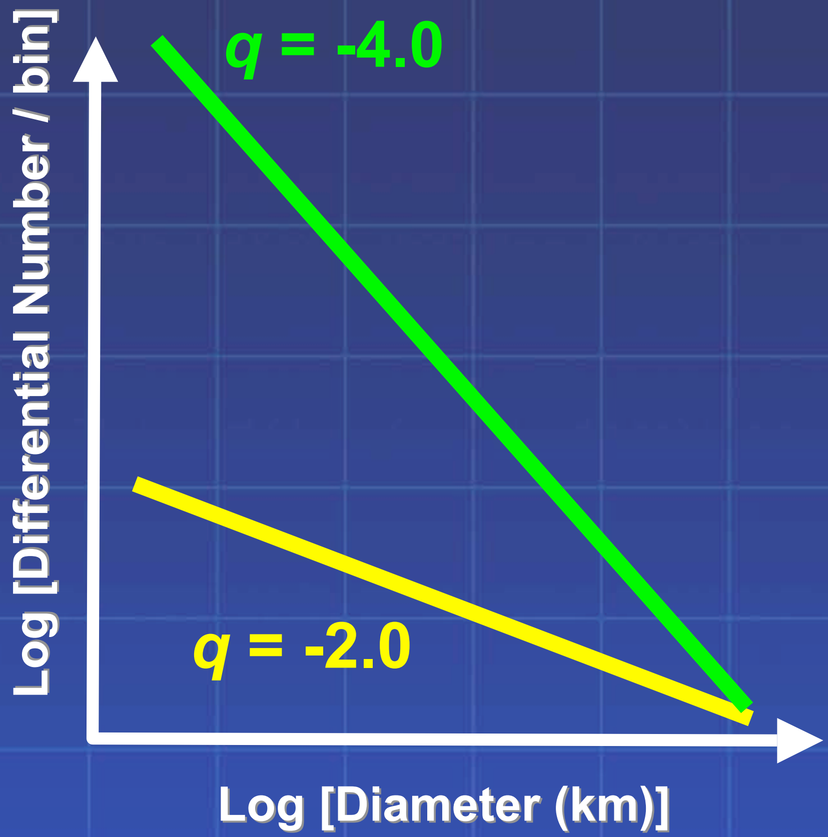


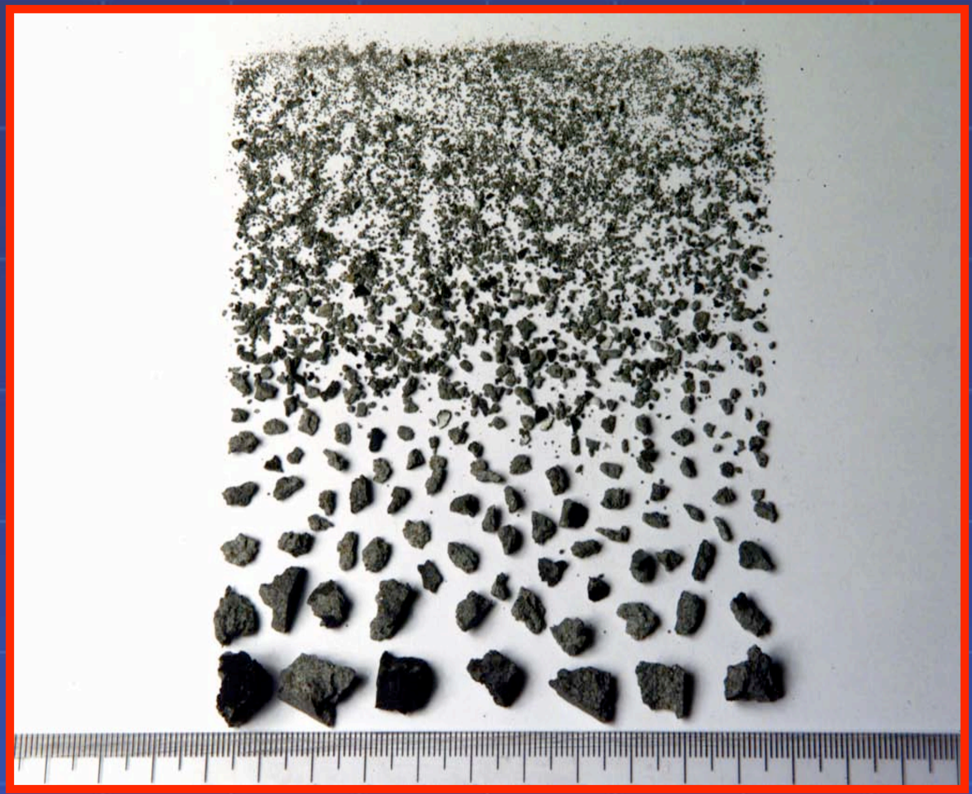
- **Chondritic additions of > 0.4% of the Earth's mass are required to provide necessary HSEs.**
- **We need a factor of 1,200 more mass for Earth than Moon!**

The Nature of Late Accretion

- The Earth/Moon see the same impacting population, with the impactors hitting in ~20:1 ratio.
- The input mass in Earth/Moon mantles need ratio of ~1,200.
- The Moon loses ~40% of projectile material upon impact. This moves Earth/Moon input mass ratio from ~1,200 to ~700 (e.g., Artemieva & Shuvalov 2008)

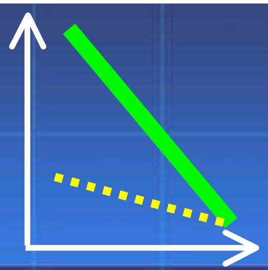
Testing Various Impacting Populations

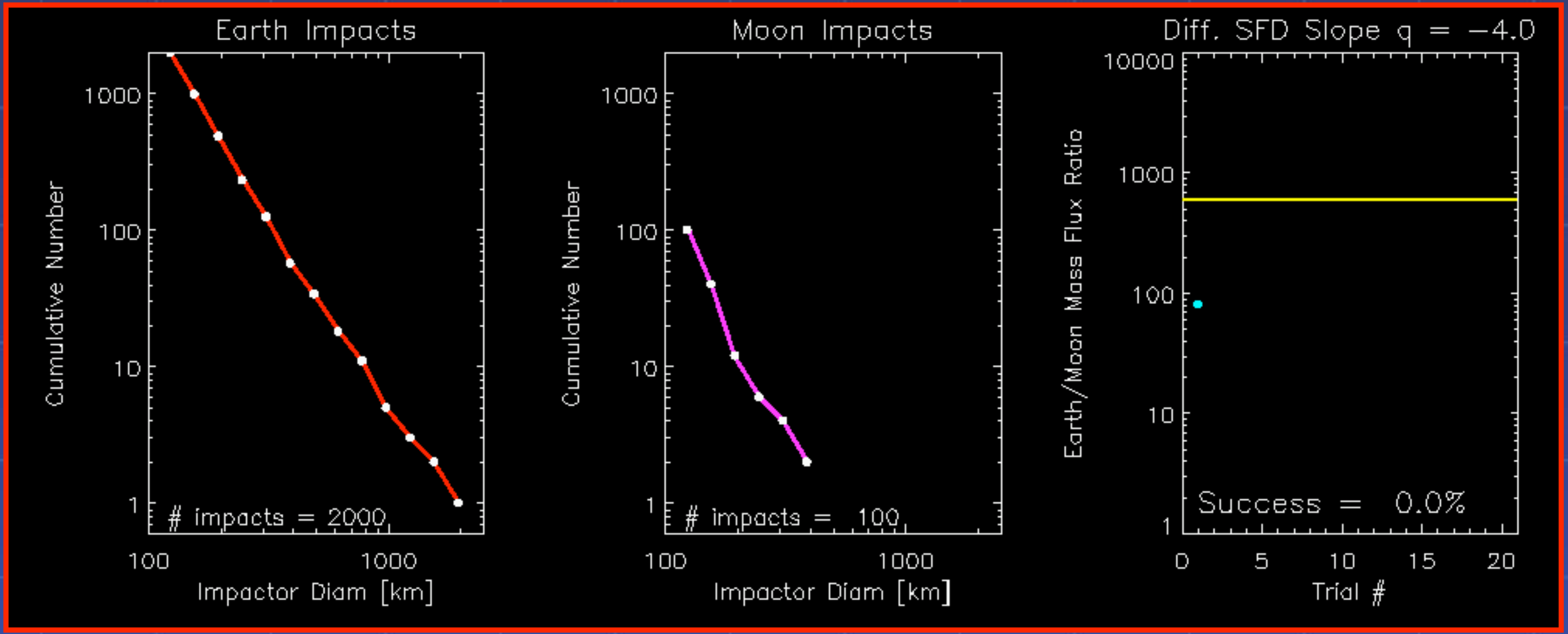




- We decided to use a Monte Carlo code to test how different impacting populations affect the Earth and Moon.

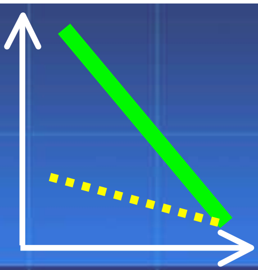
Model #1
Many Impactors, Steep SFD

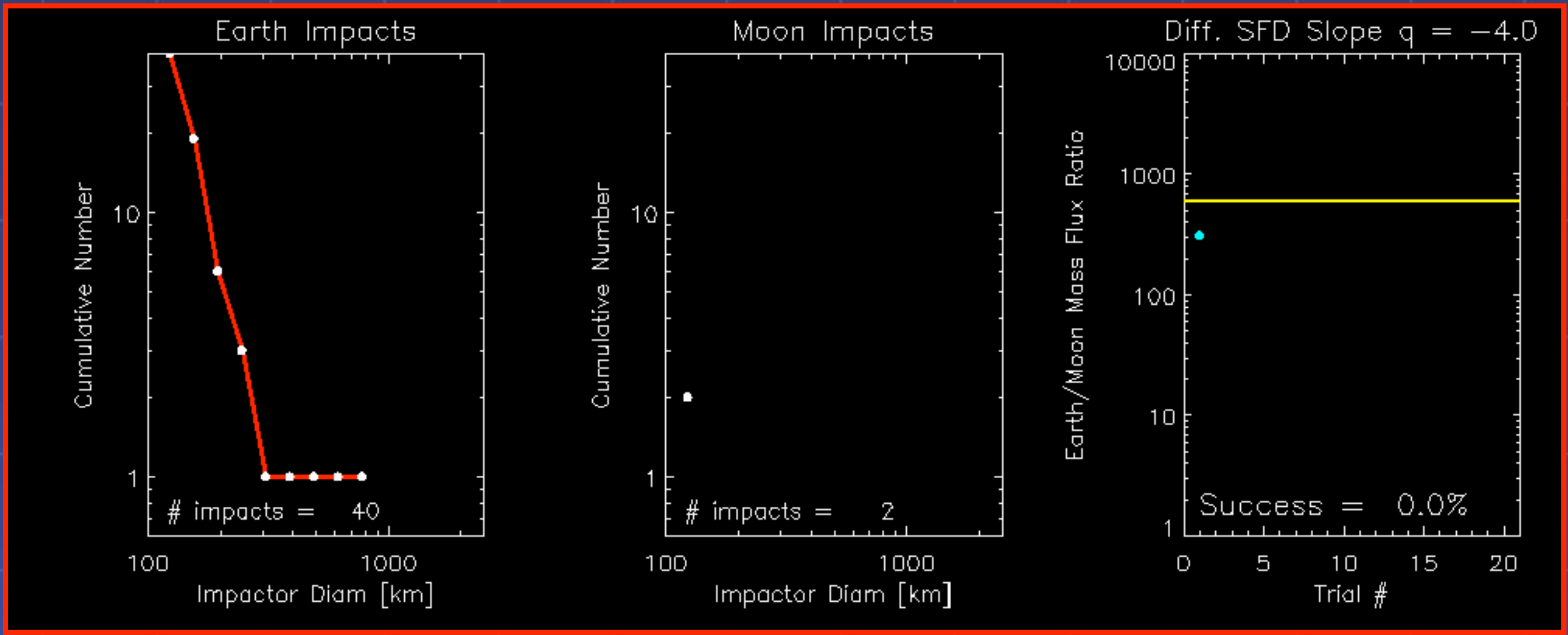




- Lots of tiny impactors (q = -4) does not yield a high input mass flux ratio.

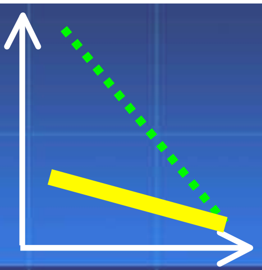
Model #2
Few Impactors, Steep SFD

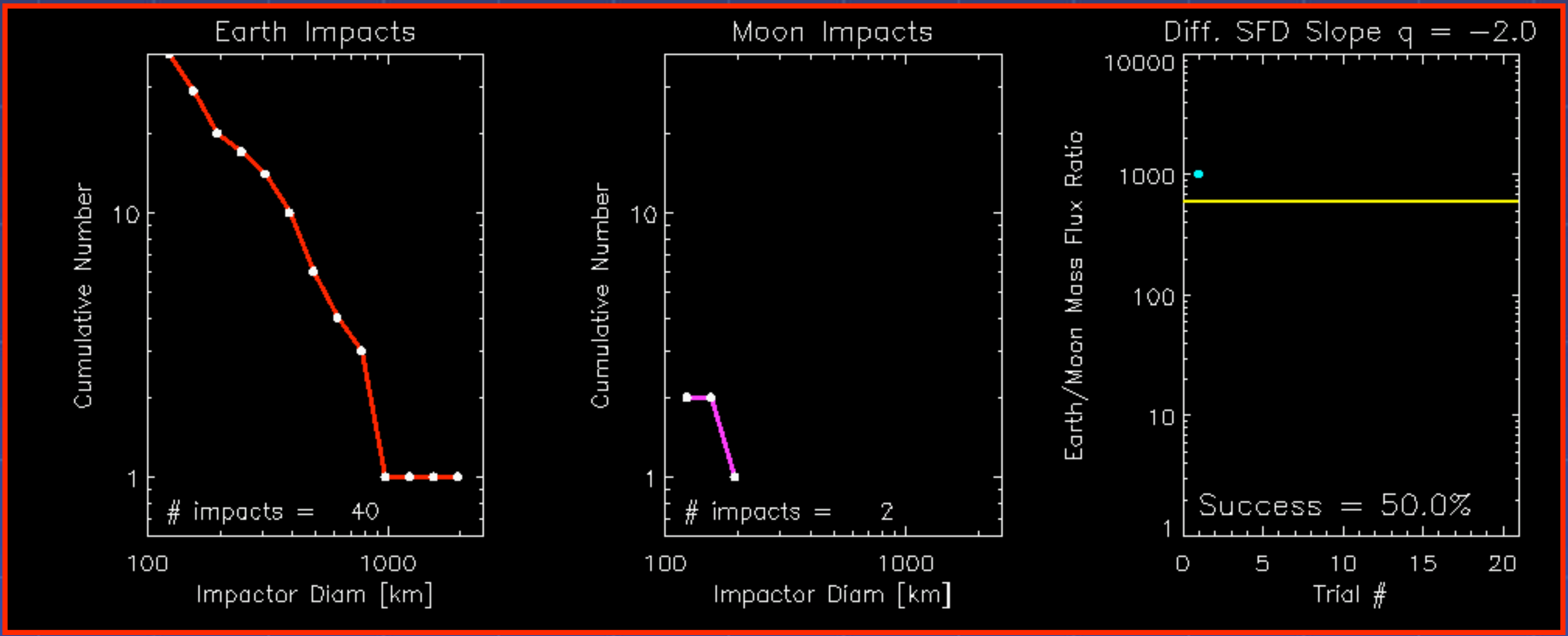




- Fewer impactors with steep size distribution (q = -4) also does not work. But…
- Stochastic variations yield mass ratios approaching ~700.

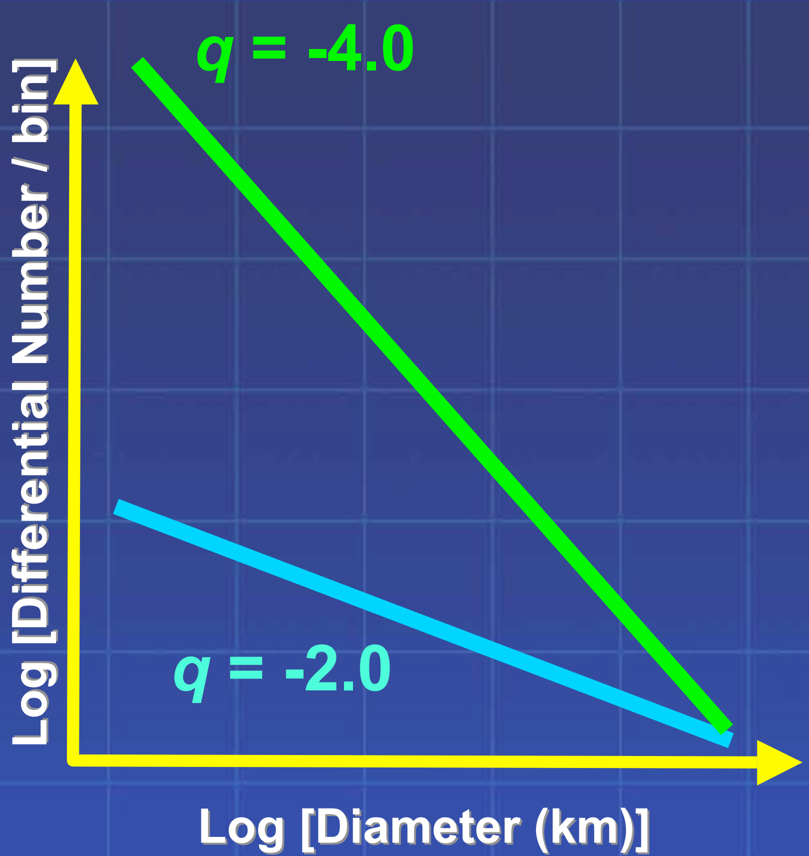
Monte Carlo Model #3
Few Impactors, Shallow SFD

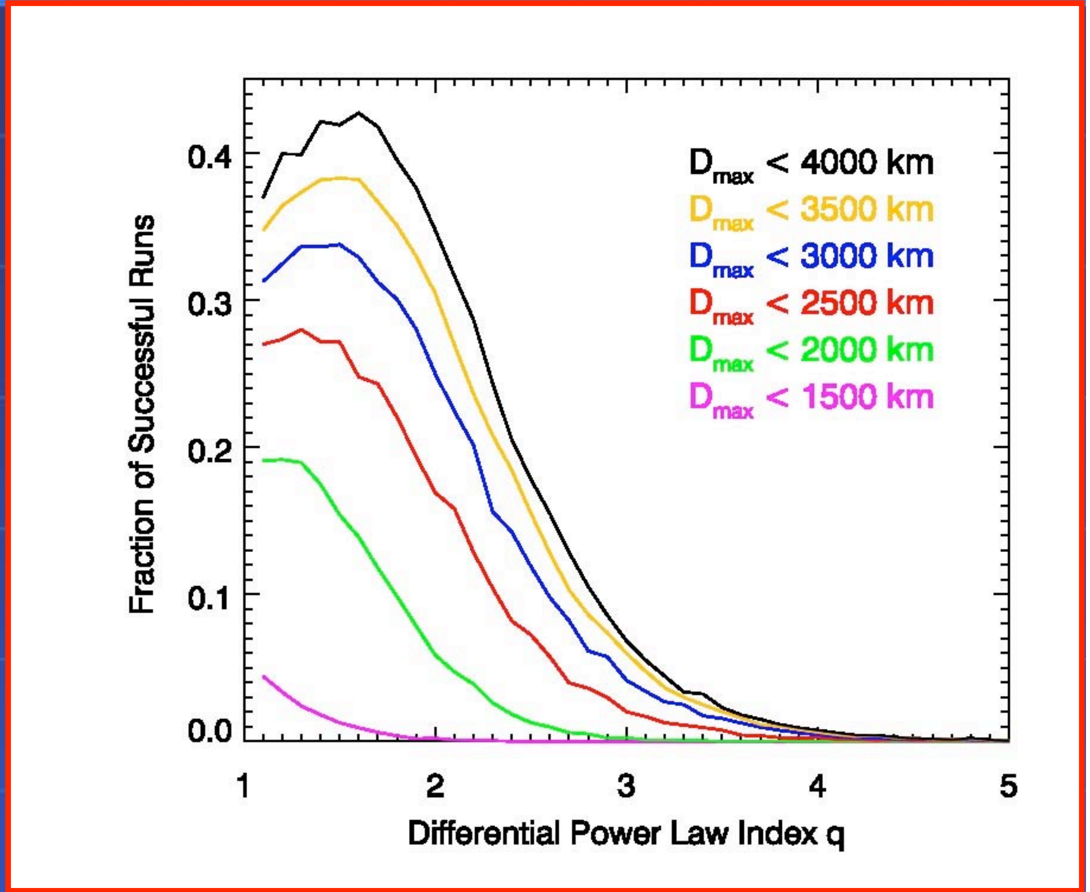




- Few impactors with shallow size distribution (*q* = -2).
- On average, Earth hit by large impactors that miss Moon.
- Success rate approaches 25-30%

Late Accretion May Require Shallow Size Distributions

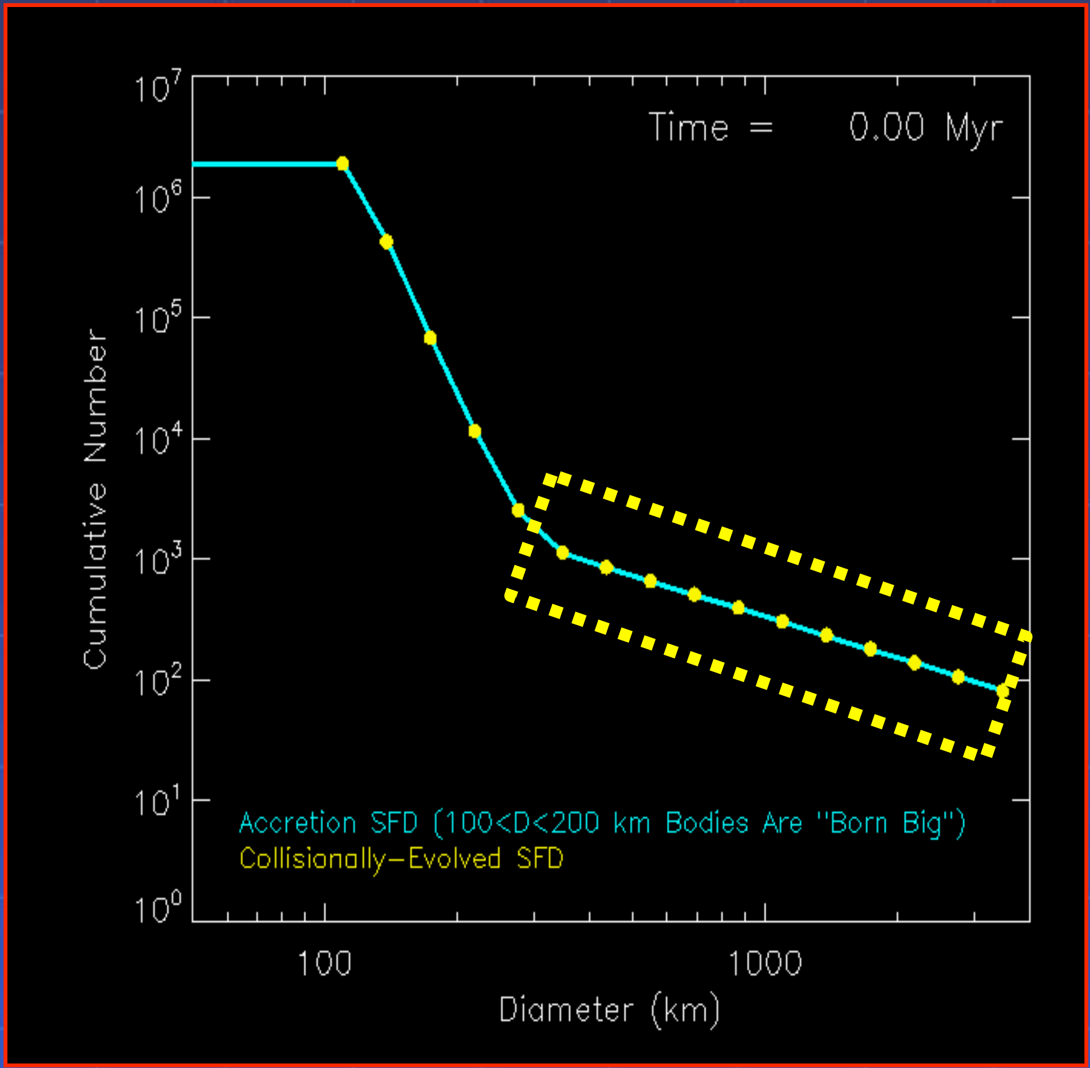




- We find that late accretion size distribution with most of their mass in largest bodies (q < -2) produces best results.

Part 4:
Evidence For a “Foot” in Late Accretion Populations

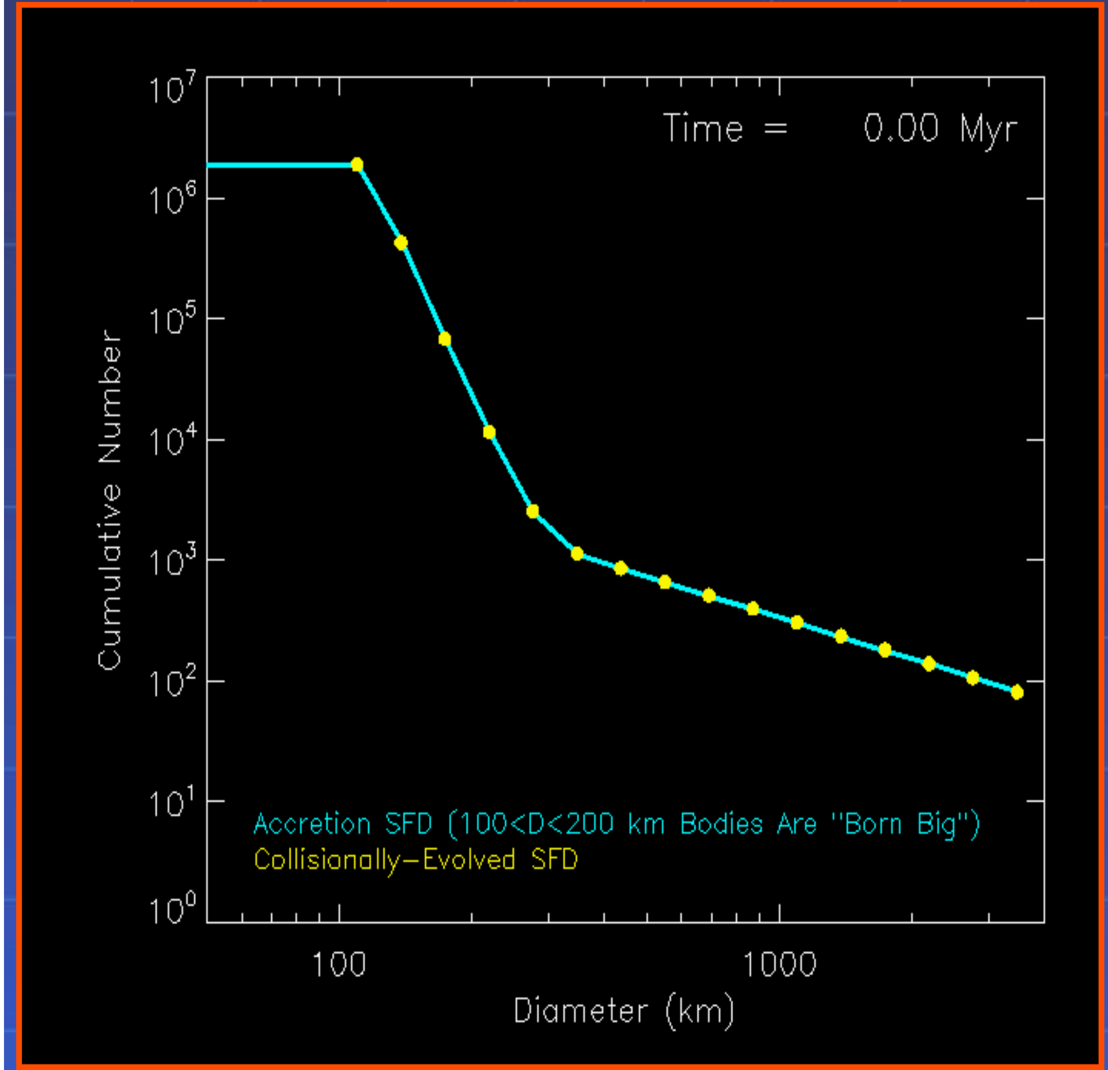
Evidence For A Shallow Late Accretion Population



Morbidelli, Bottke et al. (2009)

- New planetesimal formation models make *D* ~ 100 km bodies.
- When inserted into accretion code, it produces a shallow "foot" for *D* > 200 km.
- The "foot" is q ~ -2.

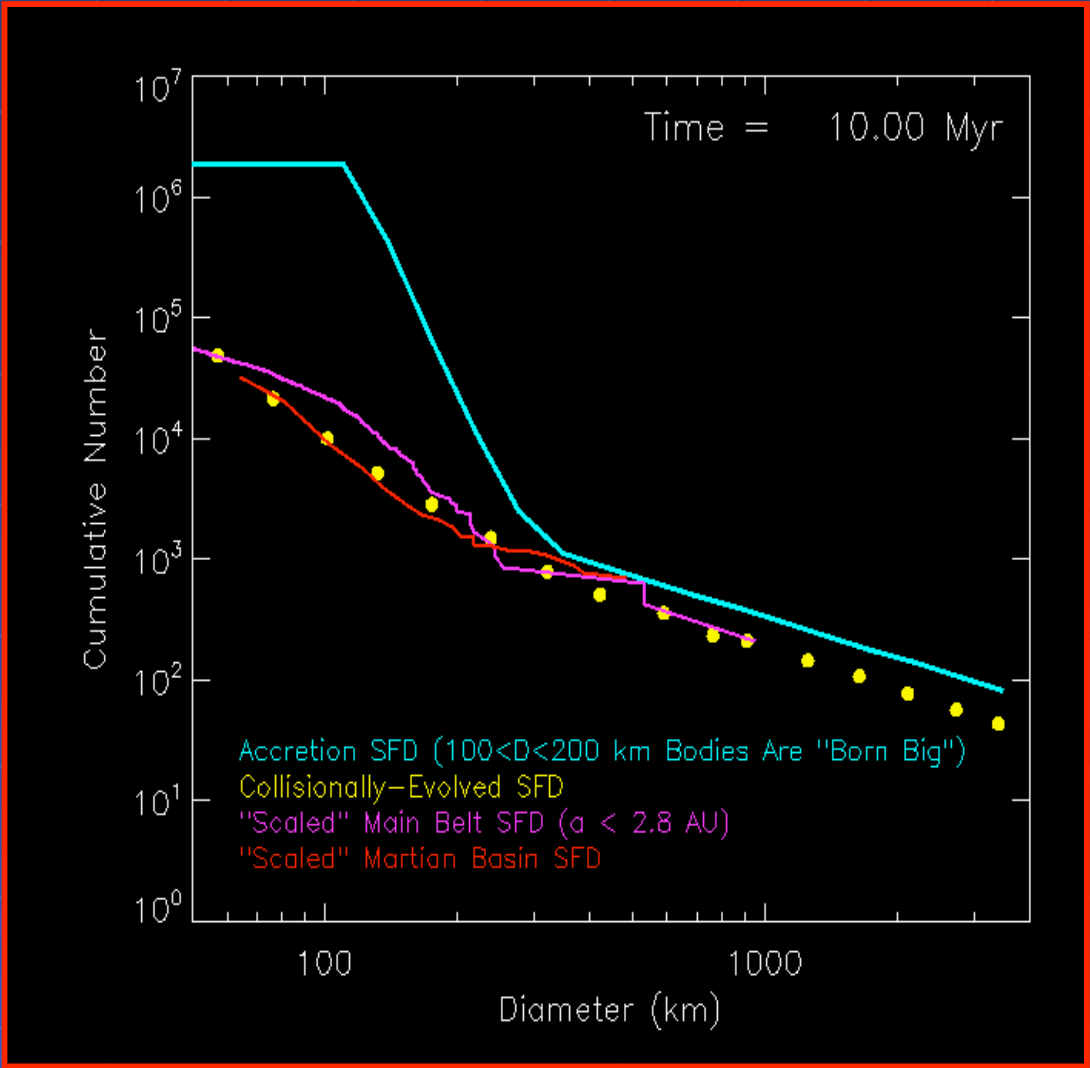
Evidence For A Shallow Late Accretion Population



Morbidelli, Bottke et al. (2009); Frey et al. (2007)

- **Accretion SFD:**
  - The "foot" is resistant to collisional evolution for runs near 1 AU.
- **Inner main belt:**
  - A "foot" exists for *D* > 250 km asteroids.
- **Martian impact basins:**
  - A "foot" is seen when basins are changed to projectile diameters.

Evidence For A Shallow Late Accretion Population



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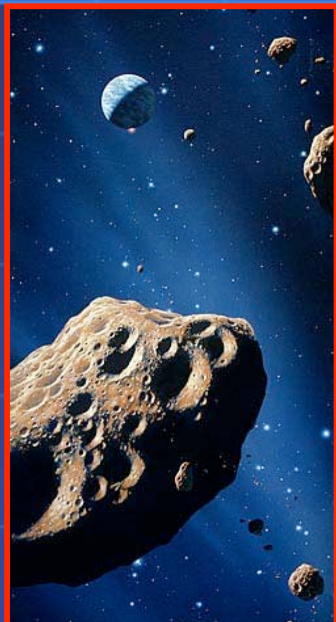
Implications:
Big Late Accretion Projectiles

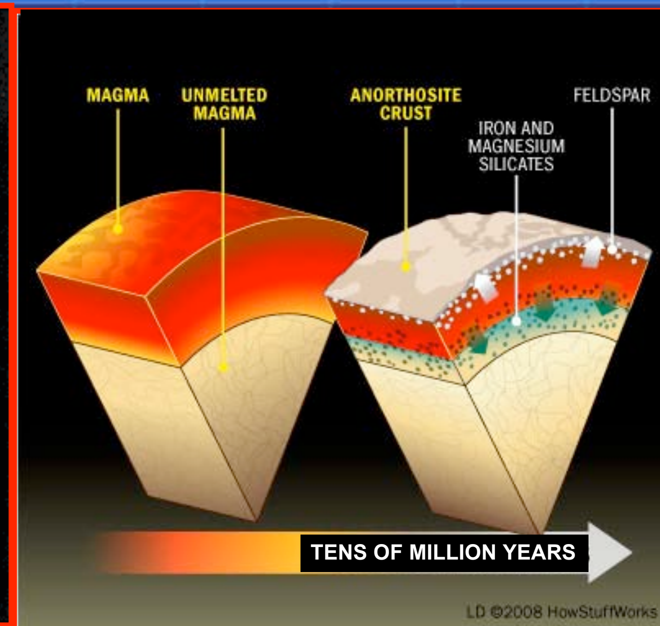
- Diameter of largest late accretion projectiles to strike Earth, Moon, and Mars:

Earth	Moon	Mars
2500-3100 km	250-280 km	1500-1800 km

  - Impact modifies Earth's obliquity by ~10°. Can this explain the inclination of Moon's orbit?
  - Lunar impactor large enough to produce South-Pole Aitken basin (or possibly Procellarum basin).
  - Martian impactor is the right size to make gigantic Borealis basin.

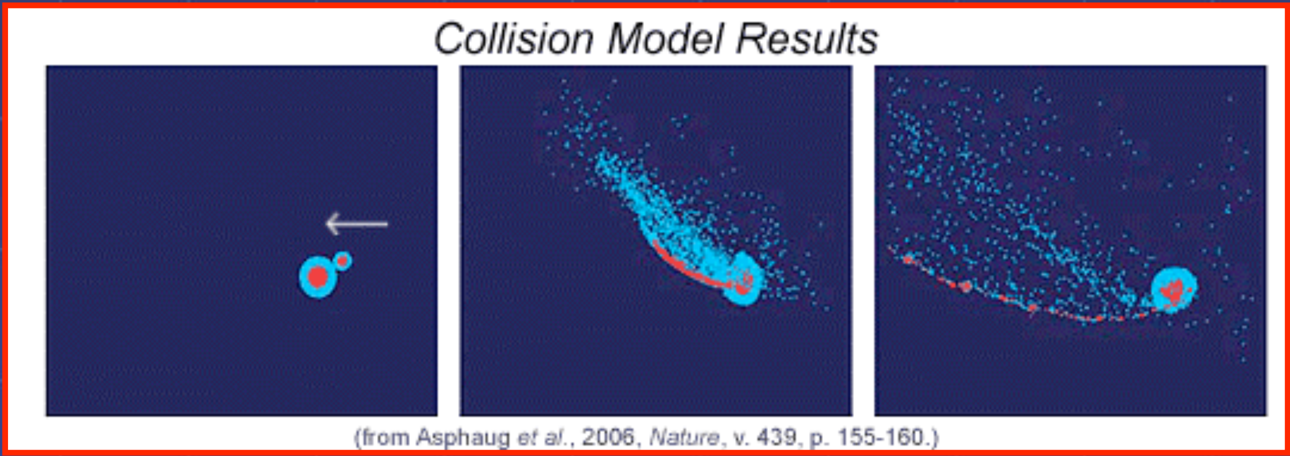
Implications:
Did Lunar Mantle Water Come from Late Accretion?

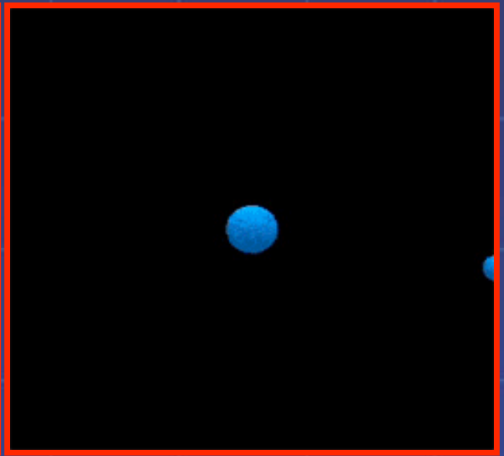




- **Assume the Moon was hit during magma ocean phase:**
  - *D* = 250-280 km projectile
  - Assume it had 0.1% water and was mixed into lunar mantle between depths of 100-500 km.
- **This yields a 1-3 ppm wt% water, the same values estimated from lunar apatites (McCubbin et al. 2010).**

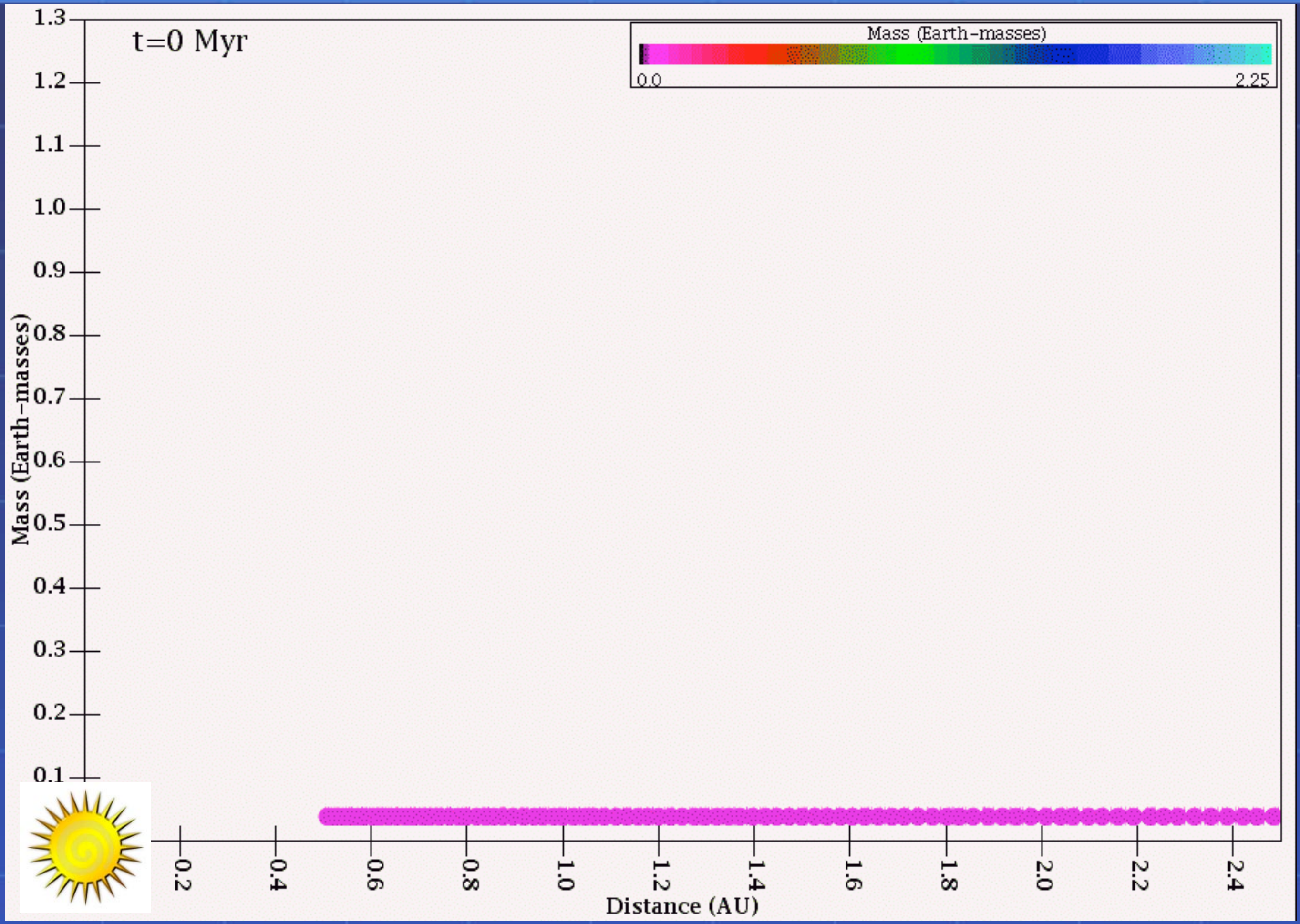
Late Accretion on the Earth: A Case of "Hit and Nearly Run"





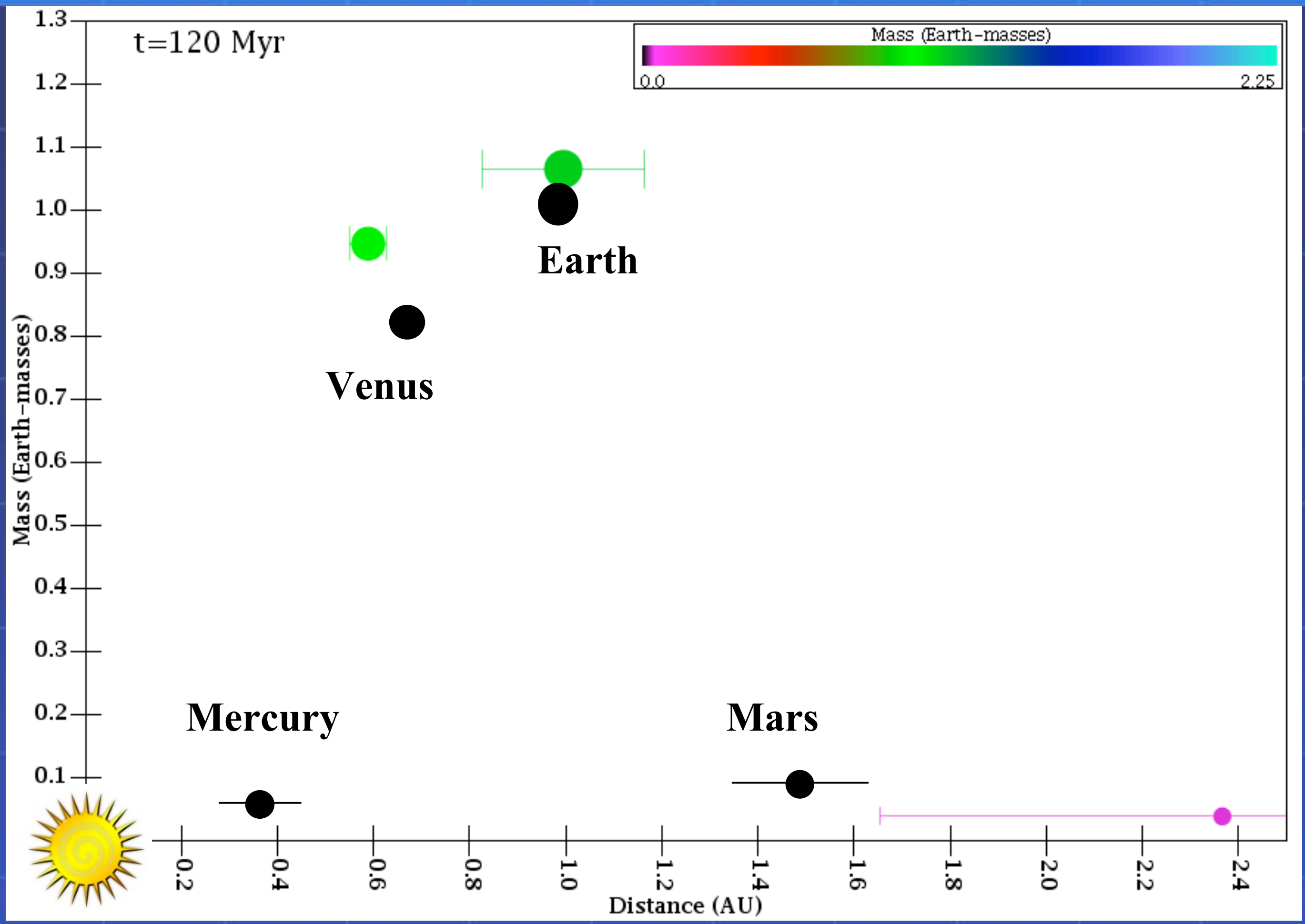
- *D* = 2500-3200 km impactors on Earth should act like "hit and nearly run" collisions.
- Most of the projectile's core escapes immediate accretion but the core fragments are eventually re-agglomerated.
- The iron and HSEs possibly emulsify into mantle immediately or are slowly incorporated into mantle via plate tectonics.

Simulated Planet Growth



- Starting with several hundred "mini-planets", collisions cause bodies to merge and form big planets!

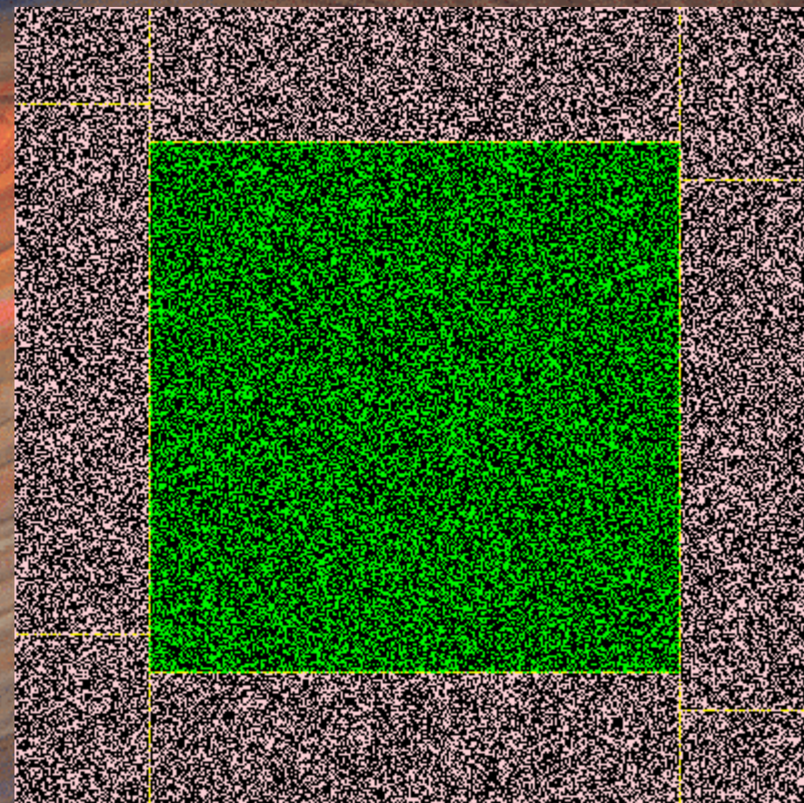
Simulated Planet Growth



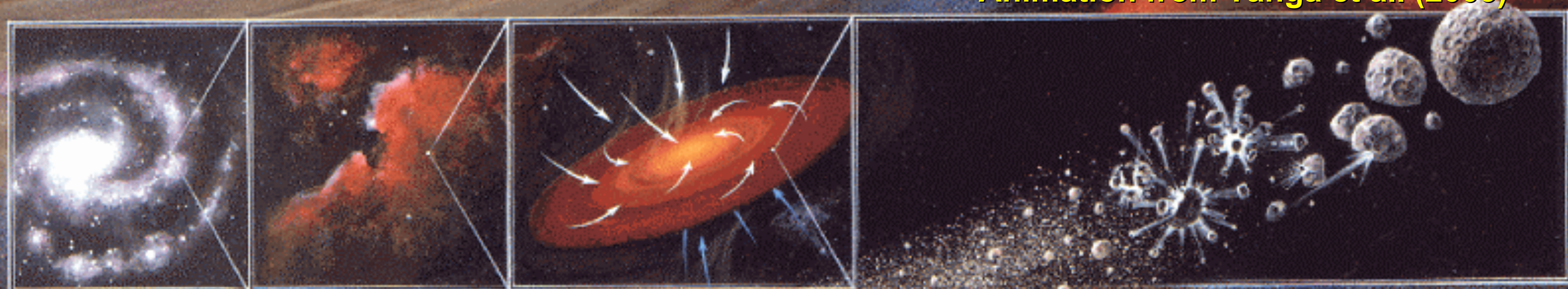
- In the end, we end up with model planets like our own.

Planetesimal Formation

- Newly-formed Sun surrounded by an orbiting disk of gas and dust.
- Disk particles come together by gravity. Collisions make larger and larger objects by “accretion”.



Animation from Tanga et al. (2003)

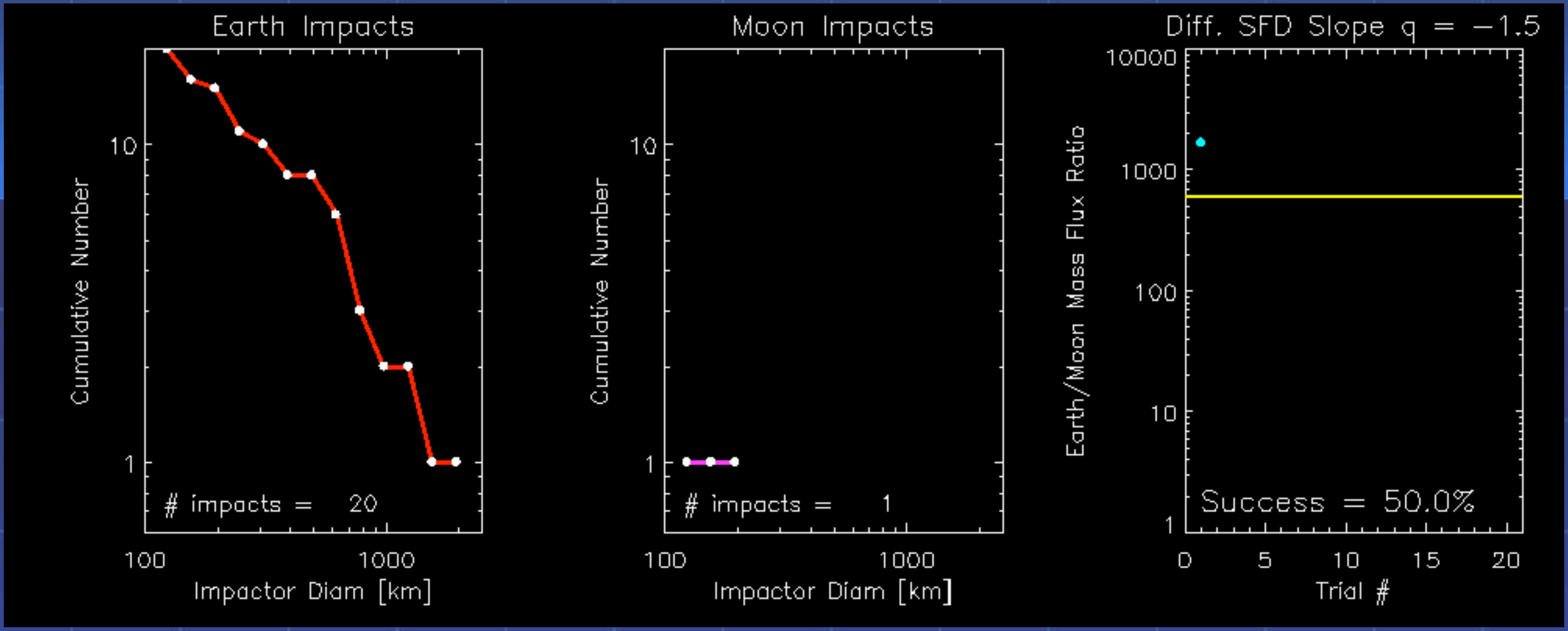


More Late Accretion Constraints

- “Pristine” lunar rocks have very low HSEs and probably dominate lunar crust. This suggests crust is unlikely to be a major reservoir of HSE.

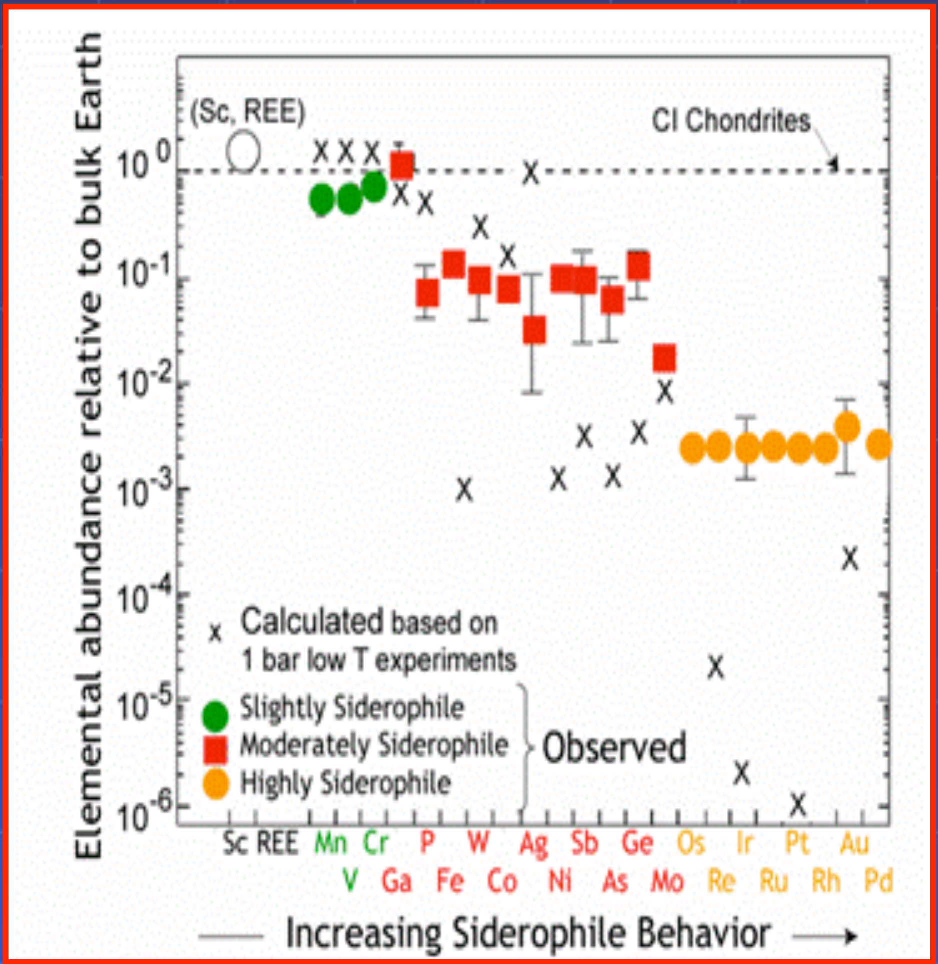
- The oldest known sample of the lunar crust formed ~100 My after CAI formation (4.46 Ga).

- Late accretion impactors need to hit within a few tens of My after Moon formation to supply HSEs.



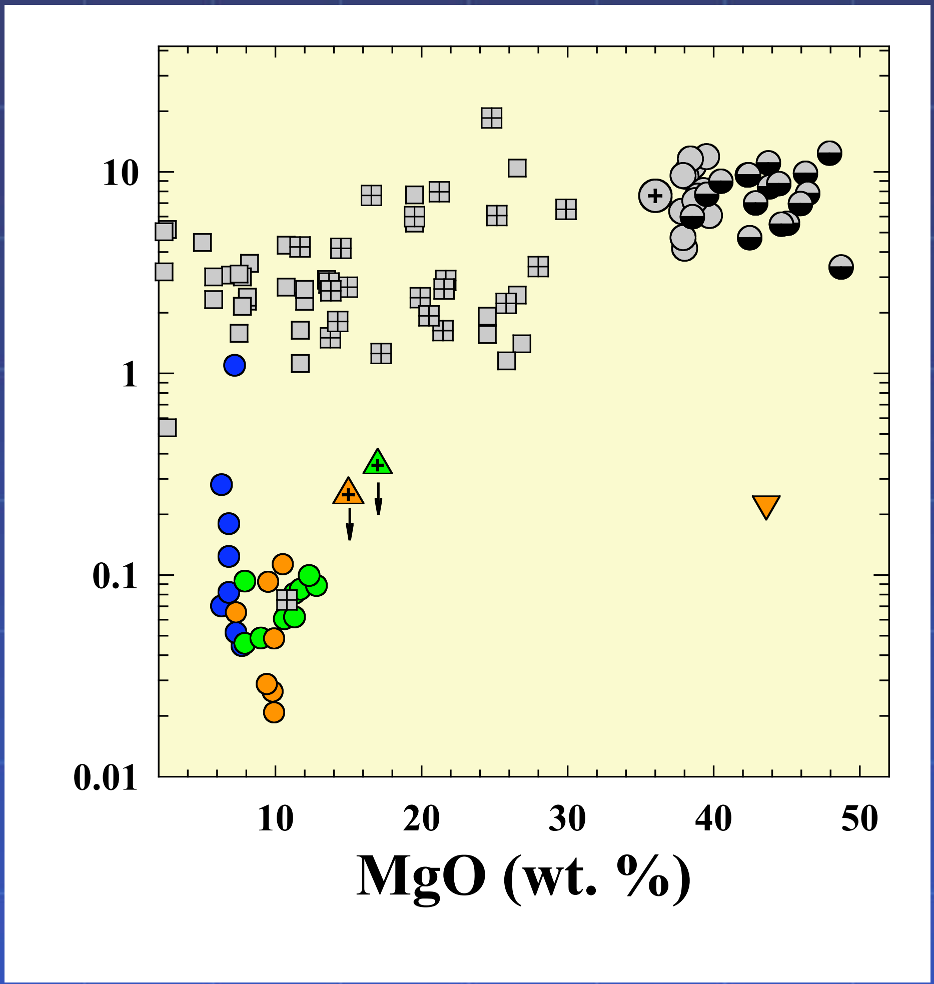
- Model 4:
- Few impactors, with a shallow size distribution (q = 1.5).
- Success rate of >50%

Highly Siderophile Elements in Earth's Mantle



- Mantle peridotites indicate Earth's ancient mantle was only depleted in HSEs by factor of ~200 compared to chondrites.
- If HSEs are mixed throughout mantle, chondritic additions of ~0.4% of the Earth's mass are required to provide necessary HSEs.

Highly Siderophile Elements in Lunar Mantle



Walker et al. (2004); Day et al. (2007)

- HSE abundances are apparently very low.
- HSE versus MgO plots consistent with >20 times depletion relative to terrestrial primitive upper mantle.

Take Away Message

- Big events on Earth and Moon are linked in time.
- The Earth and Moon have similar HSE signatures.
- The mass added to Earth was higher by factor of ~1,200!
- How do we get this?